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Ventriloquism effect with sound stimuli varying in both azimuth and elevation

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Abstract

When presented with a spatially discordant auditory-visual stimulus, subjects sometimes perceive the sound and the visual stimuli as coming from the same location. Such a phenomenon is often referred to as *perceptual fusion* or *ventriloquism*, as it evokes the illusion created by a ventriloquist when his voice seems to emanate from his puppet rather than from his mouth. While this effect has been extensively examined in the horizontal plane and to a lesser extent in distance, few psychoacoustic studies have focused on elevation. In the present experiment, sequences of a man talking were presented to subjects. His voice could be reproduced on different loudspeakers, which created disparities in both azimuth and elevation between the sound and the visual stimuli. For each presentation, subjects had to indicate whether the voice seemed to emanate from the mouth of the actor or not. Results showed that ventriloquism could be observed with larger audiovisual disparities in elevation than in azimuth.

I. STATE OF THE ART

The effect of a spatial disparity between related sound and visual stimuli can be studied in two ways (Bertelson and Radeau, 1981), either through a localization task, which makes it possible to observe *cross-modal biases*, or a discordance-detection task, which makes it possible to observe *ventriloquism* (or *perceptual fusion*).

A. Cross-modal bias

In a localization task, subjects report the direction of the sound stimulus. Significant shifts in localization towards the visual stimulus were found in many studies (Alais and Burr, 2004; Battaglia *et al.*, 2003; Bertelson and Aschersleben, 1998; Bertelson and Radeau, 1981; Hairston *et al.*, 2003; Wallace *et al.*, 2004; Bermant and Welch, 1976; Pick *et al.*, 1969; Radeau, 1974; Radeau and Bertelson, 1976; Warren, 1979; Weerts and Thurlow, 1971). For example, with a 7° difference between audio and visual stimuli in the horizontal plane, Bertelson and Radeau (1981) observed that the localization of the sound stimulus by the subjects was shifted 4° towards the visual stimulus. They also observed a deviation in sound localization of approximately 6.3° for a 15° difference between audio and visual stimuli, and observed a deviation of 8.2° for a difference of 25° . Such a phenomenon is called *cross-modal bias*.

The modality specificity hypothesis (Welch and Warren, 1980; Welch, 1999) posits

that the sensory modality with the greater precision for the discrimination to be made will dominate the percept with respect to that discrimination. Thus, the visual stimulus influences the percept of the spatial location of the sound stimulus because the visual system spatial precision is in the range of a minute arc (1/60 of a degree) (Cavonius and Robbins, 1973), while the auditory system precision is equal to or greater than 5° (Recanzone *et al.*, 1998) depending on stimulus spectrum and intensity.

In accordance with the modality specificity hypothesis, a predictive model based on maximum-likelihood estimate was successfully used in several studies to estimate the bimodal perception, relying on the precision of the auditory and visual spatial information in unimodal condition (Ernst and Banks, 2002; Alais and Burr, 2004). If a visual stimulus is perceived at a position m_V with variance σ_V^2 , and a sound stimulus at a position m_A with variance σ_A^2 , then the model predicts that an audiovisual stimulus will be perceived at a position m_{AV} so that:

$$m_{AV} = \frac{\sigma_V^2}{\sigma_V^2 + \sigma_A^2} m_A + \frac{\sigma_A^2}{\sigma_V^2 + \sigma_A^2} m_V$$

Thus, the influence of each modality on the localization of the audiovisual stimulus is weighted in proportion to the precision of the modalities in the unimodal condition.

If the visual precision decreases, then the weighting associated with m_V decreases and

the weighting associated with m_A increases: thus the audiovisual stimulus is perceived increasingly close to the sound stimulus. The model therefore suggests that situations might arise where the sound stimulus captures the visual stimulus if the visual stimulus is less salient. This "reverse" ventriloquism was observed by Alais et al. (2004). Subjects were required to localize brief light "blobs" or sound "clicks". Light "blobs" could be more or less blurred. With the sharp "blobs", visual localization was good and vision indeed dominated and captured sound. Yet, with the severely blurred "blobs", visual localization was poor and sound captured vision. For less blurred visual stimuli, neither sense dominated and perception followed the mean position between the sound stimulus and the visual stimulus.

On the other hand, if the auditory precision decreases, the visual system will dominate the percept of the spatial location of a sound stimulus even more.

B. Perceptual Fusion or Ventriloquism

In a discordance-detection task, subjects report whether or not they experience *perceptual fusion* (the so-called *ventriloquism* effect) of the visual stimulus with the related sound stimulus (Jack and Thurlow, 1973; Radeau and Bertelson, 1977; Thurlow and Jack, 1973), or, in a different version, whether they perceive the visual and sound stimuli as coming from the same or from different location (Choe *et al.*, 1975; André *et al.*, 2014; Werner *et al.*, 2013; Wallace *et al.*, 2004). Studies usually summarize the performance of

subjects by reporting the 50%-threshold (the angular difference between related visual and sound stimuli for which subjects still experience fusion - or still perceive the visual and sound stimuli as coming from the same location - half of the time). In some studies, subjects are instead asked to use the ITU-R 5-grade impairment scale (ITU-R BS.1284-1, 2003) to quantify to what extent the disparity is perceptible and annoying (Komiya, 1989; Bruijn and Boone, 2002; Melchior *et al.*, 2003, 2006; Mannerheim, 2011). As shown in Table 1, grades are associated with specific subjective impressions, and experimenters usually report either the threshold for a “perceptible, but not annoying” angular difference (Mannerheim, 2011) or the threshold for a “slightly annoying” angular difference (Melchior *et al.*, 2003, 2006). Komiya (1989) also defines the “acceptable limit of discrepancy” as the midpoint between “perceptible, but not annoying” and “slightly annoying” angular differences.

Impairment	Grade
Imperceptible	5.0
Perceptible, but not annoying	4.0
Slightly annoying	3.0
Annoying	2.0
Very annoying	1.0

Table 1: The ITU-R 5-grade impairment scale (ITU-R BS.1284-1, 2003)

Ventriloquism (observed in discordance-detection tasks) and cross-modal bias (observed in localization tasks) are two different phenomena. The relationship between them was studied by Bertelson and Radeau (1981) and Wallace *et al.* (2004), who carried out a localization and a discordance-detection task at the same time, using 50-msec pulses of either 300 Hz pure tones or broadband noise combined with LED lamps. Both studies found that biases of auditory localization towards the visual stimulus could occur even when fusion was not reported, and that biases were larger when fusion was reported.

C. Previous studies on ventriloquism in azimuth bring out several influencing factors

Numerous studies have investigated ventriloquism in azimuth (Lewald *et al.*, 2001; Komiyama, 1989; André *et al.*, 2014; Wallace *et al.*, 2004; Jackson, 1953; Thurlow and Jack, 1973; Warren *et al.*, 1981; Bertelson and Radeau, 1981; Melchior *et al.*, 2003; Mannerheim, 2011), and all came to the conclusion that the effect decreases with increasing angular difference between the positions of the sound and visual stimuli. Even so, the range of thresholds reported by those studies is wide: from 3° (Lewald *et al.*, 2001) to 20° (Komiyama, 1989). These differences can be explained by several factors: the experience of subjects, the audiovisual temporal disparity, the “compellingness” factor, and attention.

The experience of subjects

In Koimiyama's study (1989), subjects had to use the ITU-R 5-grade impairment scale to quantify to what extent the disparity between the mouth of a TV speaker and his voice was perceptible and annoying. With expert subjects, the acceptable limit of the discrepancy was 11° while it was 20° with naïve subjects. A comparison of previous studies also shows that the obtained thresholds are usually low with trained subjects ($5 - 7^\circ$ in Melchior *et al.* (2003), $4 - 8^\circ$ in Melchior *et al.* (2006), $6 - 8^\circ$ in Mannerheim (2011)) while they are always greater than 10° with naïve subjects (20° in Komiyama (1989), 18.3° in André *et al.* (2014), $> 10^\circ$ in Wallace *et al.* (2004)).

Temporal Disparity

Increasing temporal disparities between sound and image can also decrease the obtained thresholds. Using a 50-ms broadband noise burst followed by a 50-ms illumination of a LED lamp, Wallace measured a 50%-threshold greater than 15° when the delay was 200ms. However, the 50%-threshold was reduced to about 10° when the delay was 800 ms (Wallace *et al.*, 2004).

Compellingness

Ventriloquism also depends on higher level factors, such as whether or not the participant assumes that the stimuli should “go together” (Vatakis and Spence, 2007). Indeed, several studies showed that if the combinations of audiovisual stimuli are perceived as being more meaningful and “compelling”, observers will be more likely to treat them as

referring to a single audiovisual event (Jackson, 1953; Welch and Warren, 1980), and therefore to assume that they have a common spatial origin.

For example, Jackson (1953) conducted two experiments: in one, the visual stimulus was a puff of steam from a kettle whistle and the sound stimulus was a whistling sound, while in the other, the situation was much more abstract as it consisted of sounds of bells associated with lights. When the disparity between sound and image was equal to 30° , the whistling sound was still located at the kettle releasing the steam in 97% of the trials, while the sound of bell was located at the light in only 43% of the trials when the disparity between sound and image was equal to 22.5° .

In one of Thurlow's experiments (1973), a TV monitor was placed in front of the subject, and a loudspeaker was hidden 20° to the left of the TV monitor. Visual stimuli could either be a speaker reading texts, or a cross in the middle of a circle drawn on a sheet of white paper (the paper was fastened to the front of the TV monitor, with the circle approximating the location of the mouth). In both conditions, the sound stimulus was the voice of the speaker. Subjects were asked to look directly at the mouth of the speaker on the TV screen (or the cross in the middle of the circle) and to turn a stopwatch on whenever they heard speech coming from the direction of the visual stimulus and to turn it off when they did not (the stimulus was 5 minutes long). The average duration during which speech was heard coming from the visual stimulus was 3 minutes and 22 seconds

with the TV speaker and this was reduced to 51 seconds with the cross.

In Warren *et al.* (1981), the dynamic face of a speaker or a static visual stimulus (consisting of a 1×2 cm piece of tape placed at the location on the screen where the speaker's mouth would have been) was presented, together with an auditory speech signal with various degrees of spatial discrepancy. Fusion was observed for larger angles with the dynamic face than with the simple static visual spot (from 4.6° to 3.2°), because, according to Warren *et al.*, the combination of the speaker's face and the matching voice was more compelling than the visual spot with a speech signal.

Thus, 50%-thresholds will be greater with realistic sequences such as speech sequences than with arbitrary and non-meaningful combinations of stimuli, such as flashing lights and brief tones.

Attention

Several studies having conducted both discordance-detection and localization tasks suggest that focusing the attention on the spatial location of the sound stimulus makes subjects much more discriminating and thus decreases 50%-thresholds substantially. Indeed, many subjects reported noticing discrepancies only when they had to localize sound (Radeau, 1974; Radeau and Bertelson, 1976) or when they were warned that they might be questioned about the respective origins of the sound and the visual stimuli (Bertelson and Radeau, 1981). Bertelson hypothesized that humans tend to ignore the

spatial origin of auditory data to the advantage of visual data unless the task forces attention towards it. Thurlow and Jack (1973) also recommend using discordance-detection tasks instead of localization tasks, as it brings the subjects closer to an everyday life situation and prevents them from becoming excessively discriminating.

However, when Komiyama (1989) conducted his discordance-detection task, subjects reported that they would probably not have detected audiovisual discrepancies if they had not been asked to judge them. It suggests that even a discordance-detection task may make subjects too discriminating compared with an everyday life situation.

D. Ventriloquism in elevation

Ventriloquism has been extensively examined in the horizontal plane, and to a lesser extent in distance (Gardner, 1968; Mereshon *et al.*, 1980; Agganis *et al.*, 2010; Zahorik, 2003; Hládek *et al.*, 2013; Bowen *et al.*, 2011). On the other hand, few studies have explored elevation (Thurlow and Jack, 1973; Werner *et al.*, 2013).

It has been shown previously that cross-modal biases of auditory localization towards the visual stimulus become larger as the auditory precision decreases. As localization performance is poorer in the vertical plane than in the horizontal plane when stimuli are located on or near the frontal midline, one would expect to observe larger biases in elevation than in azimuth. Indeed, when Makous and Middlebrooks (1990) asked subjects to localize broadband stimuli that could vary in both dimensions, the intra-subject variability of

responses (i.e. the standard deviation of responses about the mean response location) in the vertical dimension could be as great as 2.5 times that in the horizontal dimension.

If larger biases are obtained in elevation than in azimuth, then, according to Bertelson's (1981) and Wallace's (2004) comparative studies between cross-modal bias and ventriloquism, ventriloquism should be observed with larger audiovisual disparities in elevation than in azimuth.

In one of Thurlow's experiments (1973), a TV monitor was placed on the floor, so that the mouth of the speaker on the TV screen was close to 40° below subjects' ear level. A hidden loudspeaker was positioned at an angle of 15° above subjects' ear level. Thus, the total angle between TV speaker and loudspeaker was 55° . The average duration that speech was heard coming from the TV speaker was about 4 out of 5 minutes. The duration was reduced to 1 minute and 42 seconds when the TV speaker was replaced by the unconvincing cross drawn on a sheet of paper.

In another experiment, the hidden loudspeaker was behind the subjects, at 10° above their ear level, and the TV speaker was in front of the subjects at an angle of 25° below ear level. The total elevation difference between TV speaker and hidden loudspeaker was therefore 195° . The average duration during which speech was heard coming from the TV speaker was about 3 minutes and 20 seconds, that is still two-third of the total duration of the stimulus. The average duration was reduced to 74 seconds with the unconvincing cross.

When Thurlow conducted the experiment with a hidden loudspeaker 60° to the right of the center of the TV screen (no difference in elevation), however, the average duration that speech was heard coming from the TV speaker was only 52 seconds, that is four times shorter than in the condition with a loudspeaker behind the subjects in spite of the fact that the angular difference between sound and image was reduced from 195° to 60° .

Thus, Thurlow's experiments support both the hypothesis that ventriloquism can be observed with larger audiovisual discrepancies in elevation than in azimuth, and the hypothesis that ventriloquism in elevation depends on the compellingness of the combinations of sound and visual stimuli.

In Werner's study (2013), the sound stimulus was either a 30-ms white noise burst or a 6-s anechoic recording of a saxophone, which could be reproduced via either of two virtual loudspeakers reproduced through headphones (using individualised binaural reproductions including acoustic room information). One of the loudspeakers was right in front of the subject (0° azimuth, 0° elevation) while the other one was at 25° above ear level. The visual stimuli were white LEDs positioned in front of the subject (0° azimuth) along a segment of circle centered at the subject's head, from 10° below ear level to 35° above ear level. For each presentation, subjects had to report whether they perceived the audio stimulus below, in-plane, or above the visual stimulus. Note that in this experiment, the sound stimulus was fixed while the visual stimulus was shifted. The estimated

50%-threshold was 8° for the loudspeaker at 0° elevation, whether the visual stimulus was shifted below or above the loudspeaker. For the second loudspeaker, the 50%-threshold was 10° when the visual stimulus was shifted below and greater than 10° when the visual stimulus was shifted above.

Werner concluded that the measured ventriloquism effect had similar magnitudes for elevated stimulus positions as it has in the horizontal plane. Yet, because Werner did not conduct his experiment in azimuth, this assumption is based on comparison with previous studies, whose experimental conditions were different. As ventriloquism is highly dependent on experimental conditions (see I.C), one cannot know whether the obtained similarities of thresholds does not actually result from different test designs.

In Werner's study, many factors may have favored the collection of low 50%-thresholds:

- Subjects were well experienced with listening tests and had been trained. It has been shown that thresholds obtained with experts could be half that obtained with non-expert subjects (Komiyama, 1989);
- Sound and image were presented synchronously;
- The combinations of stimuli were not compelling, as they consisted of 30-ms white noise bursts combined with white LEDs. A recording of saxophone was also used,

which can seem more realistic. Yet the recording was still associated with the white LEDS, so the combination of sound and image was probably no more compelling in this case;

- The sound stimulus was fixed (at either 0° or 25° elevation). Subjects may therefore have learnt where the loudspeakers were located precisely, which made them more accurate when comparing with the position of the visual stimulus.

Had Werner's experiment been conducted in azimuth in the same conditions, thresholds could have been much lower. The results may therefore underestimate the strength of ventriloquism in elevation compared with in azimuth.

E. Summary and aim of the present study

Numerous studies in azimuth have revealed several factors influencing ventriloquism: the spatial disparity (the effect decreases with increasing angular difference), the temporal disparity (the effect is stronger if the sound and visual stimuli are synchronous), the experience of subjects (experts are more discriminating than naïve subjects) and the “compellingness” factor (the effect is stronger if the combination of the sound and visual stimuli is more realistic).

It has also been shown that ventriloquism is dependent on the auditory system spatial precision (the effect is stronger as the auditory precision decreases). As localization

performance is poorer in the vertical plane than in the horizontal plane, 50%-thresholds are expected to be greater in elevation than in azimuth.

Thurlow's studies seem to support this hypothesis, although he did not measure 50%-thresholds so his results cannot be compared with the literature. On the other hand, Werner did measure 50%-thresholds in the median plane that had similar magnitudes as in previous studies in the horizontal plane. However, this similarity may be rather due to the specificity of his experimental conditions, and only a comparison with 50%-thresholds in azimuth obtained in the same experimental conditions would be truly legitimate.

Several studies also suggest that ventriloquism will be more likely to occur if subjects pay less attention to the spatial location of the sound stimulus. For example, in a real life speech situation, the attention would rather be focused on the semantic content, which may severely reduce subjects' attention to sound localization.

The aim of the present study is to compare ventriloquism in azimuth and in elevation in realistic conditions. It is hypothesized that:

- 50%-thresholds are greater in elevation than in azimuth. Thus, 50%-thresholds were measured for sound stimuli varying in both azimuth and elevation, so that ventriloquism in both dimensions could be compared directly;
- 50%-thresholds can be greater than in Werner's study if the experiment is conducted in conditions that more closely resemble our everyday experience: compelling

combinations of stimuli (speech sequences), naïve subjects instead of trained experts and focus of attention on the semantic content of the stimuli.

II. EXPERIMENTAL SETUP

A. Stimuli

The program material was the screening of a speaker sitting on a chair on a black background, pronouncing 5-second sentences. The sequences were shot in stereoscopic-3D using a Panasonic AG-3DP1 camera and projected in real size. The choice of stereoscopy was motivated by Ijsselsteijn’s findings that stereoscopy increases the sense of presence (Ijsselsteijn *et al.*, 2001). It was therefore hypothesized that subjects in the present experiment would assume more easily that the voice and the mouth of the speaker had a common spatial origin if their subjective sensation of “being there” with the speaker was stronger.

The phrases used in the experiment were inspired by the speech corpus used in studies on speech-on-speech masking (Martin *et al.*, 2012). The stimuli consisted of one sentence, in French, following the format “Je m’appelle {nom}, ma couleur préférée est le {couleur} et j’habite à {ville}” (“My name is {name}, my favorite color is {color} and I live in {city}”). There were three possible names (Antoine, Clément, Pierre), three possible colors (Red, Green, Blue) and three possible cities (Bordeaux, Lyon, Marseille). With all possible

combinations of names, colors and cities, the sentence could therefore take twenty-seven different forms. The stimuli were recorded in a sound-attenuated room following Bolia's recommendations (2000), with a DPA 4006 microphone connected to a RME Fireface 800. The microphone was placed 22 cm above the mouth of the speaker so that it would not be in the frame of the camera.

B. Reproduction Setup

The test took place in a sound-attenuated room of dimensions $5.10 \times 4.40 \times 3.30$ m at the University of Brest. The lights were turned off in order to minimize the influence of any visual stimuli. The subject sat at the center of the room. Head position was fixed by a chin clamp.

The image was displayed by an Epson EH-TW6000 projector on an acoustically transparent screen, with Epson ELPGS01 3D active glasses. The width and the height of the screen were 130 cm and 73 cm respectively. Playback, commands and data capture were controlled by a software implemented in Max/MSP on a MacBook Pro computer connected to a RME MADIface USB.

The system was composed of twenty-eight Amadeus PMX4 loudspeakers fed by a D.O.Tec Andiamo 2.DA MADI to analog converter through Audac DPA154 amplifiers. Each loudspeaker was digitally filtered to compensate for the transfer characteristics of the

presentation system. For each presentation, the voice of the speaker was randomly reproduced by one of the loudspeakers at a sound level of about 65 dB (A-weighted).

C. Placement of Loudspeakers

Several studies have obtained left-right symmetry for the ventriloquism effect (Werner *et al.*, 2013; Wallace *et al.*, 2004) and it was therefore decided to set all the sound stimuli to the right of the visual stimulus.

In the median plane, however, Werner's results (2013) suggest an imbalance between positive and negative discrepancies (the obtained 50%-thresholds are likely to be different whether the sound stimulus is shifted above or below the visual stimulus). Nonetheless, only positive elevations (sound stimuli shifted upwards) were studied in order to keep the test within a reasonable duration.

A two-dimensional double pole spherical coordinate system (with θ and ϕ defined as azimuth and elevation respectively) was used to describe positions of loudspeakers and 50%-thresholds on a 2.40-m sphere centered at the subject's head. Note that this coordinate system differs in its definition of azimuth from the single-pole system that is sometimes used (see Knudsen and Konishi (1979) and Middlebrooks *et al.* (1989) for a discussed comparison between the two systems).

The visual stimulus was displayed on a screen directly in front of the subject, so that

the mouth of the speaker corresponded to 0° azimuth, 0° elevation, at a distance of 2.40 m.

The sound stimulus could be shifted from the visual stimulus along several circle arcs that were also centered at the subject's head, and whose angle at the visual stimulus with the arc subtending azimuth was noted δ and defined as *orientation*. In order to keep the test within a reasonable duration, four values were chosen for δ : 0° (shifting to the right), 45° (in diagonal), 67.5° and 90° (upwards). The four δ -orientations are presented in Fig. 1.

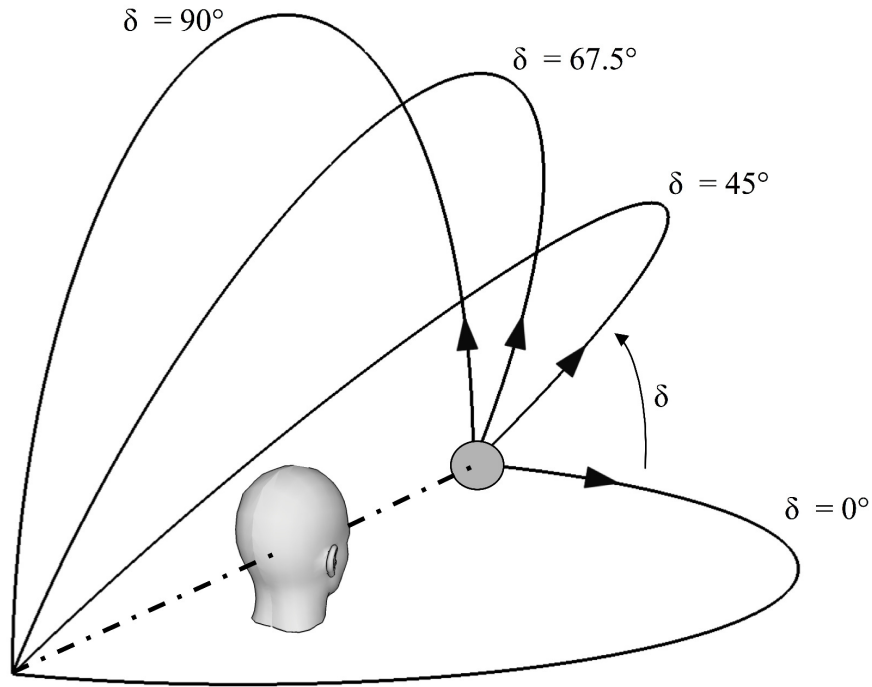


Figure 1: The four δ -orientations along which the sound stimulus could be shifted from the visual stimulus. The orientations were centered at the subject's head. The visual stimulus was fixed (0° azimuth, 0° elevation) and is represented by the grey circle.

For each δ -orientation:

- A *fusion report* refers to a situation where a subject indicates that he perceives the voice and the mouth of the speaker as coming from the same direction;
- The *angular difference* Ψ is defined as the angle at the subject's head between the visual stimulus (the mouth of the speaker projected right in front of the subject) and the sound stimulus (the voice of the speaker);
- The *50%-threshold* $\Psi_{50\%}$ is defined as the value of Ψ for which the percentage of fusion reports is equal to 50% (that is the angular difference Ψ for which the voice of the speaker is perceived as coming from the direction of the mouth half of the time);
- The 50%-threshold $\Psi_{50\%}$ can be broken down into the corresponding azimuth and elevation differences between sound and image: The *50%-threshold azimuth* $\theta_{50\%}$ and the *50%-threshold elevation* $\phi_{50\%}$.

Fig. 2 gives the example of a loudspeaker A positioned along the δ -orientation 67.5° , with an angular difference of $\Psi = 36^\circ$.

Polar coordinates can be calculated from δ and Ψ using the following formulae:

$$\text{Azimuth} : \theta_A = \arcsin(\sin \Psi \times \cos \delta) = \arcsin(\sin 36^\circ \times \cos 67.5^\circ) \approx 13^\circ$$

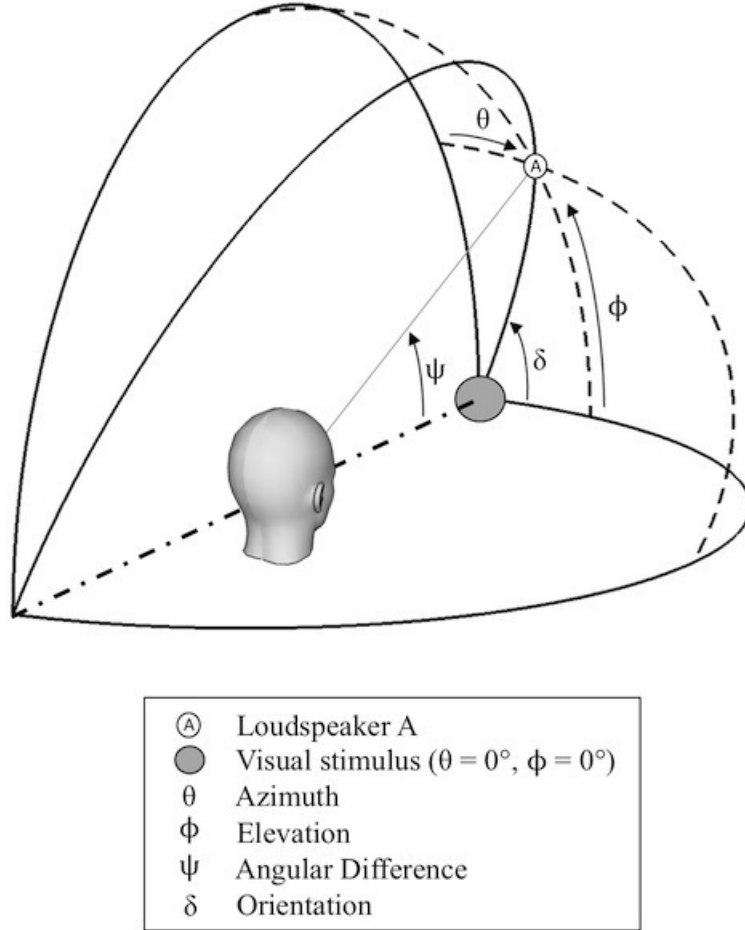


Figure 2: Example of a loudspeaker A with orientation $\delta = 67.5^\circ$ and angular difference $\Psi = 36^\circ$.

$$Elevation : \phi_A = \arcsin(\sin \Psi \times \sin \delta) = \arcsin(\sin 36^\circ \times \sin 67.5^\circ) \approx 32.9^\circ$$

The aim of the experiment was to define the 50%-threshold $\Psi_{50\%}$ for each δ -orientation. By placing loudspeakers along each of the four δ -orientations (seven loudspeakers per orientation), four psychometric functions could be estimated, from which

50%-thresholds and slopes (gradient of the psychometric function at the 50%-point) were then calculated.

Let us suppose that $\Psi_{50\%} = 32^\circ$ for the δ -orientation 67.5° . $\Psi_{50\%}$ can be broken down into the corresponding azimuth and elevation differences:

$$\theta_{50\%} = \arcsin(\sin 32^\circ \times \cos 67.5^\circ) \approx 11.7^\circ$$

$$\phi_{50\%} = \arcsin(\sin 32^\circ \times \sin 67.5^\circ) \approx 29.3^\circ$$

This means that if a loudspeaker is positioned at azimuth $\theta = 11.7^\circ$ and elevation $\phi = 29.3^\circ$, fusion will occur 50% of the times when the sound stimulus is reproduced via that loudspeaker.

The values for δ were determined on the basis of an informal test conducted by the four experimenters, which suggested that the 50%-threshold $\Psi_{50\%}$ varies moderately from orientations 0° to 45° and more substantially from orientations 45° to 90° .

Note that maintaining the loudspeaker locations at constant angles of orientation means that azimuth and elevation variations are constrained as the angular difference Ψ increases along one of the δ -orientations:

- When $\delta = 0^\circ$, there is no variation in elevation as Ψ increases (horizontal plane);

- When $\delta = 45^\circ$, azimuth and elevation vary similarly as Ψ increases;
- When $\delta = 67.5^\circ$, elevation increases faster than azimuth as Ψ increases;
- When $\delta = 90^\circ$, there is no variation in azimuth as Ψ increases (median plane).

A pilot informal test with six subjects was conducted in order to gain an idea about the general shape of the psychometric functions, from which optimal loudspeaker placement and spacing along each orientation were determined on the basis of recommendations by Lam (1999) and Levitt (1971). Levitt, for example, stated that a typical “rule of thumb” is for the experimenter to place the observations so as to roughly cover the range of expected X_{10} to X_{90} , where X_{10} and X_{90} are the stimulus levels corresponding in the present study to 10% and 90% of fusion reports.

Loudspeaker locations used in the experiment are presented in Table 2. Note that the seventh loudspeaker of the δ -orientation 90° had an angular difference Ψ of 137° , which means it was behind the subjects.

Because of the screen and room configuration, the loudspeakers could not always be placed at an exact distance of 2.40 m from the subject. The maximum distance error was 16% (the loudspeaker right above the subjects, at $\phi = 90^\circ$), which falls within the distance discrimination thresholds obtained by Ashmead *et al.* (1990) for a stimulus at 2 m, in a

Loudsp.	Orientation $\delta = 0^\circ$			Orientation $\delta = 45^\circ$			Orientation $\delta = 67.5^\circ$			Orientation $\delta = 90^\circ$		
	θ	ϕ	Ψ	θ	ϕ	Ψ	θ	ϕ	Ψ	θ	ϕ	Ψ
1	5	0	5	7.1	7.1	10	4.2	10.2	11	0	10	10
2	10	0	10	10.5	10.5	15	7.5	18.4	20	0	19	19
3	14	0	14	13.3	13.3	19	10.7	26.6	29	0	27	27
4	18	0	18	15.4	15.4	22	13	32.9	36	0	34	34
5	23	0	23	17.4	17.4	25	16	41.7	46	0	43	43
6	27	0	27	20	20	29	18.5	50	56	0	90	90
7	31	0	31	24.6	24.6	36	22.5	67.5	90	0	137	137

Table 2: Loudspeaker locations, with associated azimuth θ , elevation ϕ and angular difference Ψ , for the four δ -orientations.

control condition in which intensity was held constant over varying distance. The impact on subjects' answers was, therefore, expected to be negligible.

D. Subjects and Protocol

Eight naïve subjects took part in the experiment (four men and four women, aged 19 to 40 years old). They were financially compensated for their participation, and none of

them had particular experience in laboratory listening tests.

A first test (task A "without semantic question") was carried out in which, after each presentation, subjects had to answer the question: "Do the voice and the mouth of the actor come from the same direction?". Once they had given their answer, the next stimulus was automatically played.

An additional test was carried out with questions on the semantic content of the sequences (task B "with semantic questions"): after each presentation, subjects had to report the name, the favorite color and the living place of the speaker before giving their answer to the question on audiovisual coherence. In case of wrong answers, the trial was repeated a bit later.

As recommended by Lam *et al.* (1999), subjects went through thirty trials per loudspeaker for each task. The loudspeakers were presented in a randomized order (so as to appear as unrelated sound stimuli from multiple locations and orientations), with a different randomization for each subject. For each trial, a stimulus was randomly chosen out of the twenty-seven possible combinations of names, colours and cities. Each task was divided into two sessions of one hour each and all the subjects completed the two tasks on four different days. Subjects A, B, C and D started with task A while subjects E, F, G and H started with task B.

III. RESULTS

To estimate the psychometric functions, a nonparametric approach was used based on local linear fitting. This method has the benefit of making no assumptions about the true model underlying the data (except its smoothness) while providing better or equal performances compared with common parametric models (Zchaluk and Foster, 2009).

For task B, it was decided to remove from data the trials on which subjects answered some semantic questions incorrectly, as the error rate was very low (less than 1% for each subject).

A. Influence of the δ -orientation

Fig. 3 presents the 50%-threshold $\Psi_{50\%}$ as a function of the δ -orientation for each subject during task A (without semantic questions). $\Psi_{50\%}$ could not always be determined at $\delta = 90^\circ$: for subjects B and F, the percentage of fusion reports was greater than 50% for any loudspeaker of the orientation (fusion reports still occurred 85% and 77% of the time respectively when the angular difference Ψ was at its maximum value 137°). The value 137° was chosen for the graph, but fusion might still have occurred more than half of the time for greater angles, maybe even for the whole median plane.

Fig. 4 (results of subject C at $\delta = 90^\circ$) shows another example where the 50%-threshold $\Psi_{50\%}$ could not be determined accurately: as the slope of the psychometric

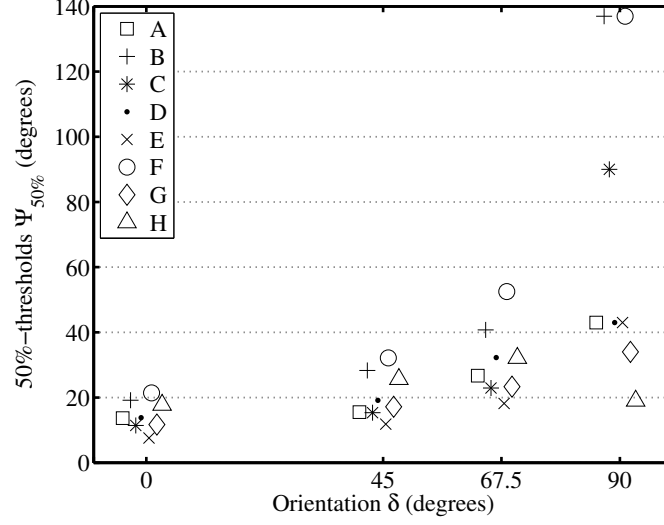


Figure 3: 50%-thresholds $\Psi_{50\%}$ for each subject as a function of the δ -orientation. Task A.

function was close to horizontal at the 50%-point, there was very little precision in the $\Psi_{50\%}$ estimate (the confidence interval was $[40.6; 107.3]$).

It was therefore decided not to use the 50%-thresholds for data obtained at $\delta = 90^\circ$, but rather to indicate the maximum value of angular difference Ψ for which fusion had been observed to occur more than half of the time. In the case of subject C, the value $\Psi = 90^\circ$, corresponding to the sixth loudspeaker of the δ -orientation 90° was reported. As the psychometric functions were monotonically decreasing for all subjects in this condition, 50%-thresholds are likely to be at values greater than those indicated.

In Fig. 3, 50%-thresholds are already spread out at orientation $\delta = 0^\circ$, ranging from 7° (subject E) to 21° (subject F), meaning that some subjects can tolerate angles three

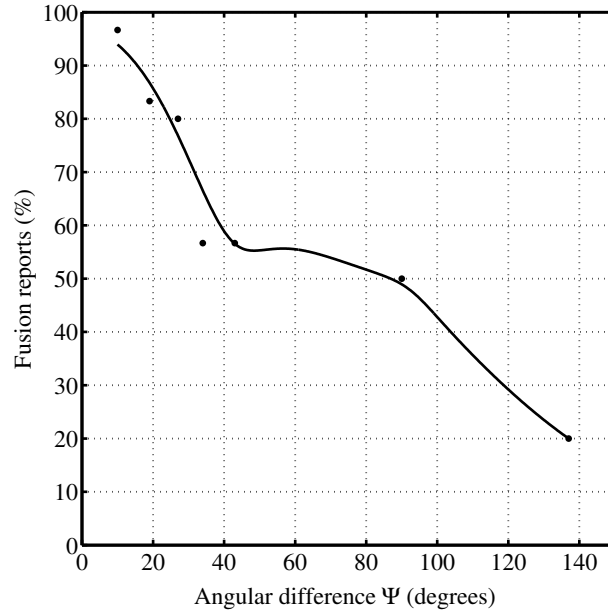


Figure 4: Psychometric function at $\delta = 90^\circ$ for subject C, task A. Points represent data obtained for each loudspeaker.

times greater than other subjects. As δ -orientation increases from 0° to 45° , all subjects show a fairly consistent trend, with a moderate increase in 50%-thresholds (mean = $+6^\circ$). As δ -orientation increases from 45° to 67.5° , 50%-thresholds increase faster for all subjects (mean = $+10^\circ$, which means that the mean increase is almost twice as much as from $\delta = 0^\circ$ to $\delta = 45^\circ$, though the difference in orientation is halved). Nonetheless, the rate of this increase varies greatly from one subject to another: for example, the increase is $+20^\circ$ for subject F whereas it is only $+6^\circ$ for subjects G. These different rates widen inter-subject variability: at $\delta = 67.5^\circ$, two subjects (B and F) present much greater thresholds (41° and

53° respectively) than the other subjects (from 18° to 32°). As δ -orientation increases from 67.5° to 90°, 50%-thresholds increase even faster for most subjects, with a greater difference in the rates of increase: +96° for subject B, but only +12° for subject G. As a result, widely spread out thresholds are obtained at δ -orientation of 90°: from 19° for subject H to 137° for subjects B and F. Subject H is the only case where, surprisingly, the 50%-threshold decreases by 9.5°. Note that subjects A, D and E present the same threshold at δ -orientation of 90°, equal to 43°. However, this equality is due to our specific definition of threshold in that orientation: the real 50%-thresholds are most likely different from one subject to another and may be spread along a range from 43° (fifth loudspeaker of the orientation) to 90° (sixth loudspeaker of the orientation).

A similar trend was obtained for task B, which included semantic questions (see Fig. 5), though the shift between $\delta = 67.5^\circ$ and $\delta = 90^\circ$ is less pronounced. Again, some subjects (A, C, D and E) present the same threshold at δ -orientation of 90°, equal to 34°, which means that the real 50%-thresholds are most likely different from one subject to another and may actually be spread along a range from 34° (fourth loudspeaker of the orientation) to 43° (fifth loudspeaker of the orientation).

In summary, results from both tasks A and B show that :

- 50%-thresholds strictly increase as δ -orientation increases from 0° to 90° (except for subject H);

- The rate of the increase depended on the subject, which widens inter-subject variability as δ -orientation increases from 0° to 90° . At $\delta = 0^\circ$, 50%-thresholds are already spread out (from 7° to 21°), yet this variability is moderate compared with that at orientation $\delta = 90^\circ$, where 50%-thresholds range from 19° to 137° .

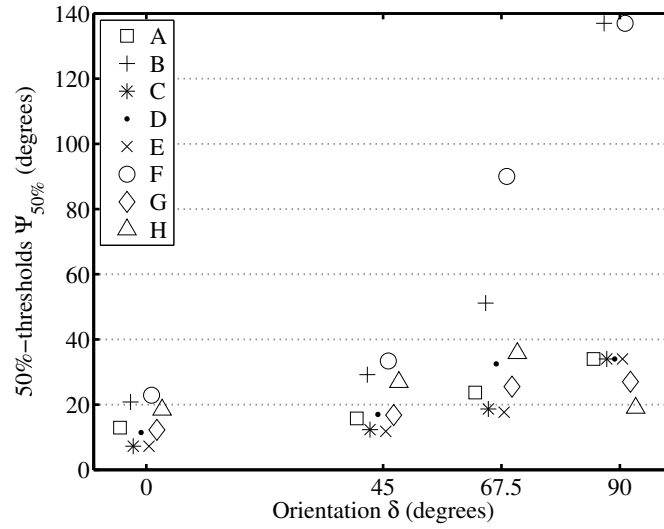


Figure 5: 50%-thresholds $\Psi_{50\%}$ for each subject as a function of the δ -orientation. Task B.

B. Influence of the task: “Without semantic questions” (task A) vs. “With semantic questions” (task B)

Wilcoxon tests were carried out to determine whether the task had a significant impact on subjects’ responses.

A first test was performed, comparing 50%-thresholds and slopes obtained for $\delta = \{0^\circ, 45^\circ, 67.5^\circ\}$. It revealed that task had no significant influence ($p = 0.976$ for

50%-thresholds and $p = 0.224$ for slopes). Another Wilcoxon test was performed for the $\delta = 90^\circ$ orientation, which compared the percentage of fusion reports obtained for each loudspeaker (see Fig. 6). The test was pooled across the seven loudspeakers of the orientation, including results from all subjects, and revealed that there were more fusion reports during the task A “without semantic questions” ($p = 0.011$), with 64% of fusion reports for task A against 59% for task B “with semantic questions”.

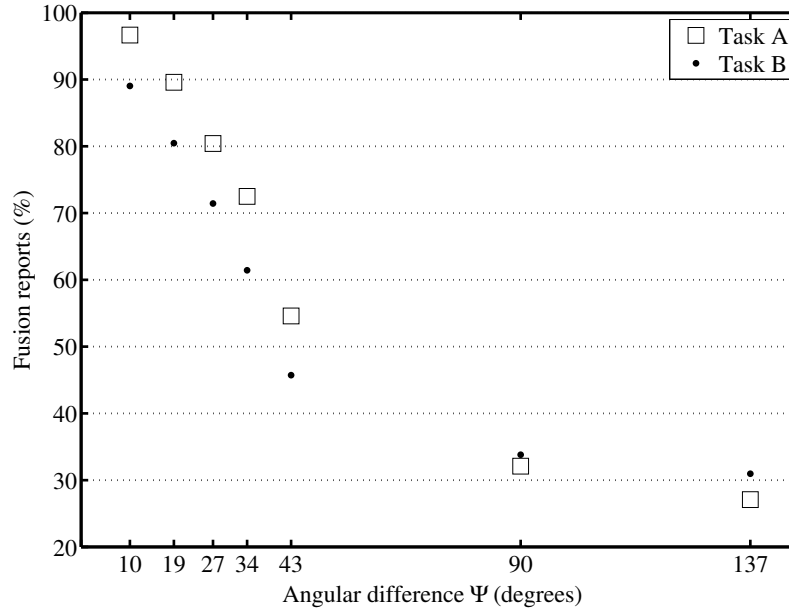


Figure 6: Percentage of fusion reports for each loudspeaker at δ -orientation of 90° , pooled across all subjects.

C. Influence of azimuth and elevation

Fig. 7 presents the 50%-thresholds $\Psi_{50\%}$ broken down into corresponding azimuth $\theta_{50\%}$ and elevation $\phi_{50\%}$ for task A.

Changes in azimuth at threshold are quite slight compared to changes in elevation at threshold as δ -orientation increases. A Wilcoxon test, pooled across tasks A and B, even shows that there is no significant difference of azimuth between orientations $\delta = 0^\circ$ and $\delta = 45^\circ$ ($p = 0.820$). Note that the δ -orientation of 45° constrains elevation to be equal to azimuth. However, if the study had not been limited to constant orientations, it is likely that 50% thresholds would have been observed at the same azimuth but with greater elevations.

At a certain orientation between $\delta = 45^\circ$ and $\delta = 67.5^\circ$, the 50%-threshold azimuth $\theta_{50\%}$ starts decreasing. Yet, as can be seen on Fig. 7, this decrease is slight compared with the simultaneous increase of the 50%-threshold elevation $\phi_{50\%}$.

Thus, fusion only depends on the azimuth difference between the visual and sound stimuli over a broad range of orientation (from $\delta = 0^\circ$ to at least 45°). Beyond 45° , elevation difference must also be taken into account, yet it requires large changes in elevation compared with azimuth to alter fusion significantly.

IV. DISCUSSION

A. 50%-thresholds are greater in elevation than in azimuth

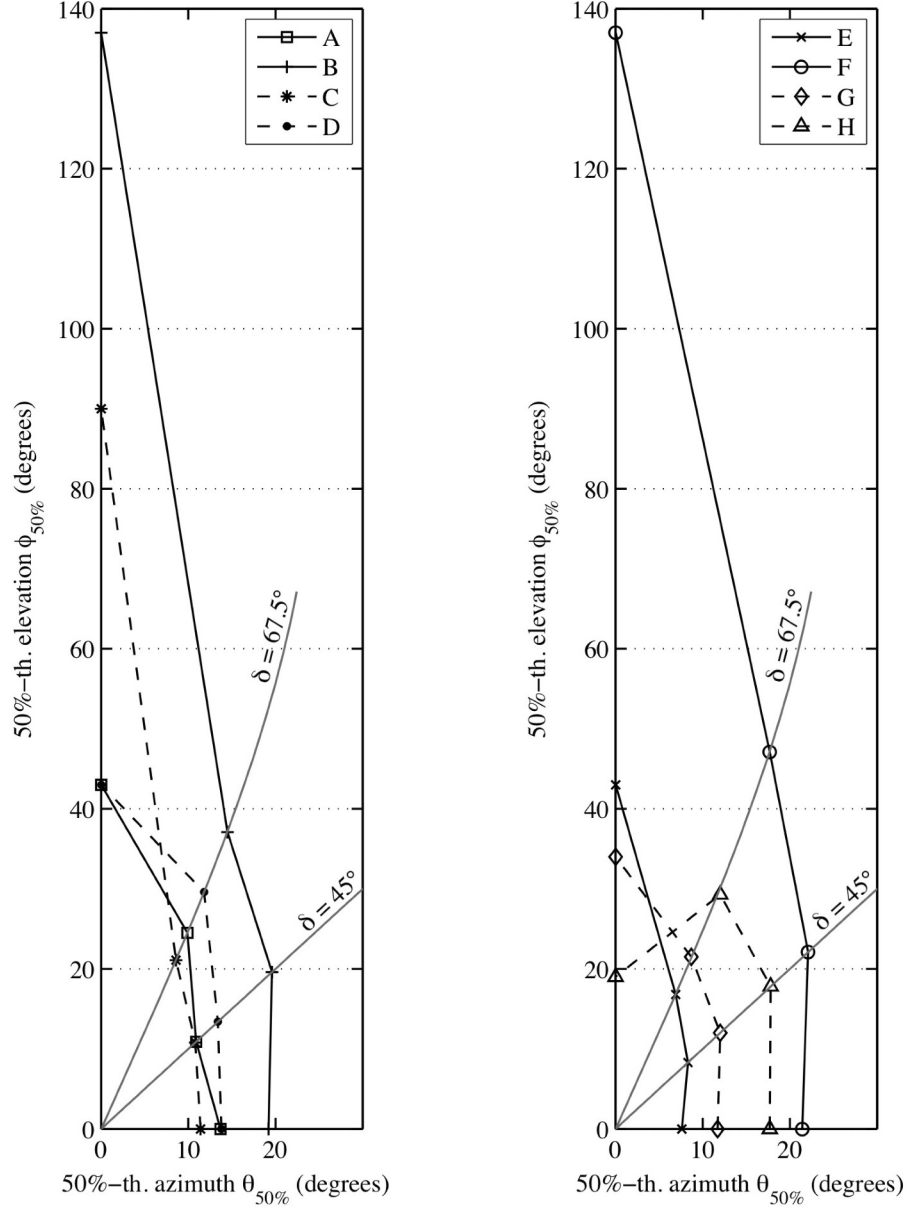


Figure 7: 50%-threshold azimuth $\theta_{50\%}$ and elevation $\phi_{50\%}$ for subjects A, B, C and D (left) and subjects E, F, G and H (right). Task A. For clarity, results were split between two diagrams. The x-axis corresponds to the δ -orientation 0° while the y-axis corresponds to the δ -orientation 90° .

The results of the present study support the hypothesis that 50%-thresholds are greater in elevation than in azimuth : 50%-thresholds were on average four times greater at δ -orientation of 90° (vertical plane) than at δ -orientation of 0° (horizontal plane). These results are consistent with Thurlow's previous studies (1973), and also with the localization performance of the auditory system: as spatial precision is poorer in the vertical plane than in the horizontal plane, the influence of the spatial location of the sound stimulus decreases and thus larger angular differences are tolerated. Yet, pronounced inter-subject variability was observed, as 50%-thresholds in the vertical plane ranged from 1.1 to 8 times greater than 50%-thresholds in the horizontal plane depending on the subject. For "oblique directions" (δ -orientation of 45° and 67.5°), the visual and sound stimuli present both azimuth and elevation differences, yet results show that changes in elevation have very little effect on ventriloquism and that 50%-thresholds are mainly determined by the azimuth difference.

B. 50%-thresholds can be large in the vertical plane

It had also been hypothesized that 50%-thresholds in the vertical plane would be greater than in Werner's study if the experimental conditions were changed so as to more closely resemble our everyday experience. In the present experiment:

- Naïve subjects conducted the test instead of experts, and it has been shown that thresholds obtained with non-expert could be as great as twice those with expert

subjects;

- The experimenters sought to achieve a high degree of realism for the stimuli (stereoscopic projection of a life-size speaker), assuming that it would substantially increase the compellingness of the combination of sound and visual stimuli. In Thurlow's studies (1973), a compelling combination of sound and visual stimuli could multiply the average duration during which fusion occurred by almost three compared with a non-meaningful combination;
- In the present experiment, sound could come from twenty-eight different locations (while Werner's study only used four loudspeakers). It might therefore have been less easy for the subjects to learn the location of the sound stimuli.

Results show that 50%-thresholds in the vertical orientation were indeed much greater (from 19° to values greater than 137°) than those obtained by Werner *et al.* (2013) (between 8° and 10°). The percentage of fusion reports may even have been greater than 50% in the whole median plane for two subjects, as they still reported fusion 85% and 77% of the time even when the sound stimulus was behind them ($\Psi = 137^\circ$ at δ -orientation of 90°). These results are not unexpected: indeed, Thurlow and Jack (1973) had already observed that fusion was possible in the vertical plane in spite of a 195° angular difference between the visual and sound stimuli.

C. Variations of attention impact ventriloquism only in the median plane

It had been hypothesized that forcing the subject to focus on the semantic content of the stimuli would increase 50%-thresholds. However, most subjects reported that memorizing the name, the favorite color and the living place of the character was an easy task that did not draw their attention away from spatial disparities. Other subjects reported that the first words “je m’appelle”/“my name is” (which were the same for every sentence) were enough to make their decision on the ventriloquism question and they could therefore focus on the semantic content for the rest of the sentence. Results showed that there was indeed no significant difference between tasks A and B for $\delta = \{0^\circ, 45^\circ, 67.5^\circ\}$.

However, there were more fusion reports during the task A “without semantic questions” than during the task B “with semantic questions” at $\delta = 90^\circ$. The trend cannot result from a learning effect, as the order of the tasks was different depending on the subject. It could be hypothesized that forcing the subjects to focus on the semantic content maintains their level of arousal at a higher degree and therefore makes them more discriminating over time.

Although the results contradict the experimenters’ hypothesis, they still show that variations in the subjects’ attention can change the 50%-thresholds significantly. At $\delta = \{0^\circ, 45^\circ, 67.5^\circ\}$, those changes are negligible, but it becomes far more influential at $\delta = 90^\circ$.

D. Different weightings of influencing factors might explain the increase of

inter-subject variability as δ -orientation increases

A hypothesis, very similar to a model proposed by Thurlow and Jack (1973), could explain the observed trends.

Whether a sound stimulus fuses with a visual stimulus or not is a complex decision that depends on several factors such as the location of the sound stimulus, the extent to which a subject assumes that the sound and the visual stimuli should “go together” (compellingness factor) and the extent to which the subject pays attention to the spatial location of the sound stimulus.

The influence of these factors has more or less weight depending on the situation. For example, if the precision of sound localization is poor, then the sound stimulus could come from any one of a large number of locations. If the combination of the visual and sound stimuli is highly compelling, the subjects might assume that the most probable location for the sound stimulus is the same as the visual stimulus. Thus, the influence of the factor “location of the sound stimulus” decreases to the benefit of the “compellingness” factor.

While some factors are fairly consistent across subjects, other factors show large inter-subject variability:

- Localization performance has been shown to be consistent across subjects (Makous and Middlebrooks, 1990);

- The strength of the assumption that a sound stimulus and a visual stimulus should “go together” (compellingness factor) depends on the experience of subjects and on their history with similar situations (Warren *et al.*, 1981);
- Attention to the auditory modality has also been shown to vary substantially from one subject to another in previous visual-auditory multisensory tasks (Giard and Peronet, 1999).

Thus, if the weight associated with a highly subjective factor (such as compellingness or attention) increases, it would be expected to observe larger inter-subject variability.

In the horizontal plane, localization performance is good. Thus, as long as there is some minimal difference in azimuth between the sound and visual stimuli, whether or not fusion occurs is strongly influenced by the horizontal location of the sound stimulus. This has several consequences:

- 50%-thresholds occur for limited angular differences between the sound and visual stimuli;
- A change in elevation of the sound stimulus has little effect because the lack of precision in vertical localization makes this change an irrelevant spatial cue compared with azimuth;
- The influence of other factors such as compellingness and attention is reduced. Thus,

moderate inter-subject variability is shown, and small variations in attention (task A vs. task B) are negligible.

Yet, as δ -orientation increases, there are increasing elevation differences and decreasing azimuth differences between the sound and the visual stimuli. As localization precision is poorer in elevation, the influence of the spatial location of the sound stimulus thus decreases, which has two consequences:

- 50%-thresholds increase;
- The influence of other factors, such as compellingness and variations in attention, increases. As these factors are highly subjective, larger inter-subject variability is observed. It would also explain why the factor “attention” (task A vs. task B) only became significant at δ -orientation of 90° .

Fig. 8 shows the psychometric functions obtained for subject D during task A. The slopes determine how strongly the percentage of fusion reports varies with the angular difference Ψ . A steep slope means that the 50%-threshold clearly separates the angular difference Ψ into two zones: one where fusion always occurs, and one where fusion never occurs. As the slope gets shallower, an interval of “uncertainty” increases around the 50%-threshold, corresponding to a range of angular differences for which subjects’ judgments of fusion may change from one trial to another. In Fig. 8, the slopes are steep

and quite similar at δ -orientation of 0° and 45° . Yet, as δ -orientation increases from 45° to 90° , the slope gets shallower. This trend, which has been observed for all subjects, is entirely consistent with the hypothesis that the decision of subjects is being increasingly influenced by fluctuating factors, such as attention, as δ -orientation increases from 45° to 90° .

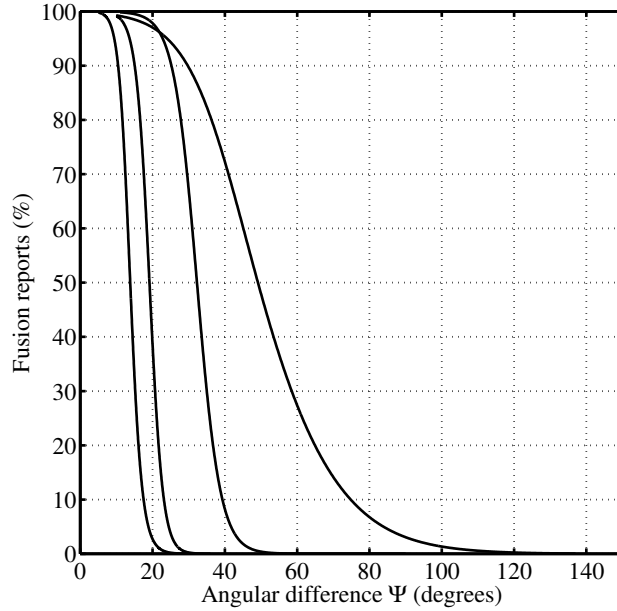


Figure 8: Psychometric functions obtained for subject D during task A at each δ -orientation. From left to right : $\delta = 0^\circ$, $\delta = 45^\circ$, $\delta = 67.5^\circ$, $\delta = 90^\circ$.

V. CONCLUSION

In the present experiment, images of a speaker were presented directly in front of subjects. The voice of the speaker could be reproduced on different loudspeakers, which

created disparities between the sound and the visual stimuli. For each presentation, subjects had to indicate whether the voice and the mouth of the speaker came from the same direction (the so-called *ventriloquism* effect) or not. 50%-thresholds were measured for sound stimuli varying in both azimuth and elevation. Results show that 50%-thresholds were greater in elevation than in azimuth (which is consistent with the localization performance of the auditory system), and could sometimes reach very high values (some subjects still perceived the voice of the speaker on his mouth, even when the sound was reproduced behind them). However, larger inter-subject variability was observed in elevation than in azimuth.

In an additional task, subjects had to answer questions on the semantic content of the stimuli before giving their answer on ventriloquism. As long as some minimal difference in azimuth between the sound and visual stimuli was present, there was no effect of the semantic questions. In the median plane (no difference of azimuth), the effect was significant but contrary to what was expected: 50%-thresholds decreased when subjects had to focus on the semantic content.

Results suggest that:

- In azimuth, fusion is mainly determined by the horizontal location of the sound stimulus relative to the location of the visual stimulus. As sound localization performances in azimuth are precise and similar across subjects, 50%-thresholds and

inter-subject variability are moderate compared with in elevation;

- In elevation, sound localization is not precise, and the influence of the location of the sound stimulus decreases substantially to the benefit of subjective factors such as attention or compellingness. Thus, greater 50%-thresholds are obtained (especially if the combination of sound and visual stimuli is realistic) and the inter-subject variability increases.

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Figure Captions

Table 1. The ITU-R 5-grade impairment scale (ITU-R BS.1284-1, 2003).

Fig. 1. The 4 δ -orientations along which the sound stimulus could be shifted from the visual stimulus. The orientations were centered at the subject's head. The visual stimulus was fixed (0° azimuth, 0° elevation) and is represented by the grey circle.

Fig. 2. Example of a loudspeaker A with orientation $\delta = 67.5^\circ$ and angular difference $\Psi = 36^\circ$.

Table 2. Loudspeaker locations, with associated azimuth θ , elevation ϕ and angular difference Ψ , for the 4 δ -orientations.

Fig. 3. 50%-thresholds $\Psi_{50\%}$ for each subject as a function of the δ -orientation. Task A.

Fig. 4. Psychometric functions at $\delta = 90^\circ$ for subject C, task A. Points represent data obtained for each loudspeaker.

Fig. 5. 50%-thresholds $\Psi_{50\%}$ for each subject as a function of the δ -orientation. Task B.

Fig. 6. Percentage of fusion reports for each loudspeaker at δ -orientation of 90° , pooled across all subjects.

Fig. 7. 50%-threshold azimuth $\theta_{50\%}$ and elevation $\phi_{50\%}$ for subjects A, B, C and D (left) and subjects E, F, G and H (right). Task A. For clarity, results were split between two diagrams. The x-axis corresponds to the δ -orientation 0° while the y-axis corresponds to

the δ -orientation 90° .

Fig. 8. Psychometric functions obtained for subject D during task A at each δ -orientation.

From left to right : $\delta = 0^\circ$, $\delta = 45^\circ$, $\delta = 67.5^\circ$, $\delta = 90^\circ$.